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A MULTISTAGED BURNER DESIGN FOR IN-FURNACE NO_x CONTROL

by

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16. ABSTRACT The paper gives results of an evaluation of a multistage combustion modification design, combining two advanced NOx control technologies, on a pilot-scale (0.9 MW) package boiler simulator for in-furnace NOx control of high nitrogen fuel combustion applications. A low NOx precombustion chamber burner, which has been reduced in size (to provide a 350 msec bulk gas residence time) to improve commercial applicability, is being used with 10-20% natural gas reburning, in which staged fuel and air are introduced at the boiler front face to reduce boiler modification requirements. Parametric test results thus far indicate that NOx emission levels can be maintained at less than 0.2 lb (calculated as NO2) per million Btu, or about 150 ppm (dry, at zero % O2), for primary fuel mixtures with up to 4% fuel nitrogen dopant. Gaseous and liquid fuels, with ammonia and pyridine dopants used to simulate fuel nitrogen, are being tested. The ongoing EPA program to further optimize burner design and operating conditions is discussed.

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Nitrogen Oxides	Coal	Stationary Sources	07B
Combustion	Wastes	Reburning	21B
Burners	Ammonia	Precombustion	13A
Boilers	Pyridines		07C
Fuel Oil			21D

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ABSTRACT

A multistaged combustion modification design, combining two advanced NO_x control technologies, is being evaluated on a pilot-scale (0.9 MW) package boiler simulator for in-furnace NO_x control of high nitrogen fuel combustion applications. A low NO_x precombustion chamber burner, which has been reduced in size (to provide a 350 msec bulk gas residence time) to improve commercial applicability, is being used with 10 to 20 percent natural gas reburning. in which staged fuel and air are introduced at the boiler front face to reduce boiler modification requirements. Parametric test results thus far indicate that NO_x emission levels can be maintained at less than 0.2 lb (calculated as NO_2) per 10^6 Btu (86×10^{-12} kg/J), or about 150 ppm (dry, at zero percent O_2), for primary fuel mixtures with up to 4 percent fuel nitrogen dopant. Gaseous and liquid fuels, with ammonia and pyridine dopants used to simulate fuel nitrogen, are being tested. The ongoing EPA program to further optimize burner design and operating conditions is discussed.

INTRODUCTION

Oxides of nitrogen (NO_x) are formed during combustion by the reduction and oxidation of molecular nitrogen and nitrogen contained in the fuel. Because NO_x emitted from stationary combustion sources contribute to the degradation of air quality as well as to acid deposition and forest damage, various control technologies have been developed to reduce NO_x emissions. Many of the NO_x control technologies currently in use involve modifications of the combustion process to reduce peak flame temperatures and create fuel-rich conditions by altering fuel and oxidizer mixing rates. These modifications frequently result in reduced combustion efficiency and increased vessel wall corrosion from soot and char. Furthermore, practical constraints, such as burner and boiler size limitations, limit the effectiveness of NO_x control by combustion modification.

In-furnace NO_x control technologies currently in use, including low-NO_x burner and overfire air injection, can achieve NO_x emissions of 100 to 600 ppm, depending on the fuel nitrogen content (Fig. 1). While these technologies are sufficient to meet current U. S. New Source Performance Standards (NSPS), new technologies will be required to meet regulations if more stringent acid rain legislation is enacted.

The U. S. Environmental Protection Agency (EPA) is currently involved in the development and field demonstration of two evolving NO_x control technologies: the precombustion chamber burner and reburning. These combustion modification strategies provide alternatives to expensive post-combustion NO_x removal technologies, such as selective catalytic reduction which is being utilized extensively in Japan and West Germany, for achieving low NO_x emissions when firing high nitrogen content fuels or incinerating highly nitrated wastes. The goal of this work is to utilize the precombustion chamber burner and reburning concepts in developing a low-NO_x, high efficiency burner that is practical for both new and retrofit installations.

BACKGROUND

Many studies have been made of the mechanisms of nitric oxide (NO) formation in flames, both from molecular nitrogen (thermal NO) and from fuel-bound nitrogen (fuel NO). Thermal NO can be reduced by decreasing flame temperatures. Fuel NO, not as strongly dependent on temperature, is very sensitive to reactant stoichiometry. Fuel-rich conditions promote molecular nitrogen (N_2) formation over fuel NO formation. Laboratory studies and field test data have established the importance of fuel NO to the total emission of NO_x from residual fuel oil and coal flames. Therefore, staged combustion (involving the formation of a fuel-rich zone by controlling fuel/air mixing) is an effective in-furnace NO_x control technique for stationary combustors.

The precombustion chamber burner is a staged combustion technology for achieving less than 100 ppm NO_x even for high nitrogen fuel combustion [1]. It consists of a primary air and fuel injection system, a large refractory wall "precombustion" chamber, and a secondary air injection section. The primary air may be preheated by channeling it along the refractory wall (Fig. 2a). Fuel and primary air are appropriately injected for rapid mixing in the near-adiabatic precombustion chamber at a first-stage stoichiometry of approximately 0.7. A fuel-rich zone residence time of 0.6 to 1.0 sec allows for maximum reduction of fuel nitrogen species. First-stage combustion gas products exit the primary zone through a convergent section which minimizes both radiative heat loss to the boiler and backmixing of the secondary air.

The precombustion chamber burner has been tested on a full-scale (16 MW_t) crude-oil-fired steam generator used for thermally enhanced oil recovery (TEOR) in Kern County, CA [2]. A 30-day continuous monitoring test demonstrated the capability of the burner to maintain continuously NO_x emissions of 70 ppm with high a combustion efficiency [3]. During burner

optimization testing, NO, CO, and smoke emissions were measured over a range of first-stage stoichiometries. These data, shown in Fig. 2b, indicate the sensitivity of NO emission to first-stage stoichiometry and the good hydrocarbon burnout characteristic of the burner.

The full-scale burner test results confirmed the scaling design criteria that were developed during bench- and pilot-scale testing. In Fig. 3 NO_x emissions from bench-, pilot-, and full-scale tests are plotted versus first-stage residence time. The data indicate that a first-stage residence time of at least 0.8 sec is necessary to produce minimum NO_x levels of about 40 to 50 ppm. Earlier pilot-scale tests firing nitrogen-free fuels suggest that this minimum NO_x level can be attributed to second-stage thermal NO formation.

While the precombustion chamber burner has been demonstrated to achieve low NO_x levels for high nitrogen fuels, its large size makes it impractical for many boiler applications. Reducing the burner size results in incomplete reduction of the fuel nitrogen in the precombustion chamber and, hence, higher NO_x emissions. However, an in-furnace NO_x control technology exists for removing NO_x from the combustion gas stream. NO_x formed in the primary flame can be destroyed by fuel staging, or reburning. By diverting portions of the fuel and combustion air streams from the main burner(s) for injection into the post-flame gases, reburning establishes a three-stage combustion process, consisting of a fuel-lean primary zone, a fuel-rich reburning zone, and a fuel-lean burnout zone (Fig. 4). NO_x is destroyed by hydrocarbon radical reactions to form intermediate fixed nitrogen species and eventually molecular nitrogen. An overall reaction pathway has been postulated by Chen et al. [4].

$$NO_x \xrightarrow{CH} HCN \longrightarrow NH_i \rightleftharpoons NH_3 \begin{cases} \xrightarrow{} NO \\ \xrightarrow{NO} N_2 \end{cases}$$

As many as 30 years ago, experimental results were available indicating that NO could be destroyed by reaction with hydrocarbon radicals. Commercial utilization of this reaction mechanism occurred in the late 1960's by the John Zink Corporation who patented a NO_x control process for nitric acid plants [5] based on staged injection of natural gas. Early fundamental studies of NO_x destruction by injection of secondary fuel into the flame zone were performed by Wendt et al. [6], who coined the name "reburning" to describe the process. Concerted effort to develop reburning for application to boilers occurred in Japan during the late 1970's and early 1980's. The first reporting of these efforts was by Takahashi et al. [7], documenting extensive laboratory-, pilot-, and full-scale evaluations of a fuel staging process they refer to as Mitsubishi Advanced Control Technology, or MACT. MACT results indicated that NO_x emissions can be reduced by at least 50 percent independent of initial NO_x level and fuel type. These promising results have renewed interest in reburning, and further development is being

sponsored by the U. S. Environmental Protection Agency (EPA), the Electric Power Research Institute (EPRI), the Gas Research Institute (GRI), and the U. S. Department of Energy (DOE).

Since 1982 EPA has carried out both in-house and extramural bench- and pilot-scale reburning tests. In-house experiments have focussed on natural gas and fuel oil reburning [8-11]. Coal reburning tests have been performed for EPA by Energy and Environmental Research Corporation [4, 12] and Acurex Corporation [13]. Significant findings include the dependence of reburning effectiveness on primary flame NO level, reburn zone stoichiometry, and reburn fuel nitrogen content. Fifty percent NO reduction is possible with 10 to 20 percent of the fuel used for reburning. At low primary NO levels, however, a nitrogen-free reburning fuel (such as natural gas) must be used to achieve 50 percent reduction. Tests have shown that reburning is effective over a wide range of temperatures and with relatively short reburning zone residence times (less than 0.2 sec).

EPA will cosponsor with GRI and EPRI a reburning application test on an industrial or small utility coal-fired boiler, beginning in late 1986 and lasting 3 to 4 years. A field application test of the precombustion chamber burner has also been initiated. Thus, independently, these technologies are nearing the final stage of development.

EXPERIMENT

The goal of this experimental study is to develop a multistaged burner design concept that utilizes a half-sized precombustion chamber burner and natural gas reburning to maintain NO_x emissions[1] of less than 150 ppm[2] for primary fuels with up to 4 percent fuel nitrogen dopant. The design is to minimize boiler modification so as to maximize retrofit potential and commercial applicability.

Apparatus and Methods

The pilot-scale test facility used in this study, shown schematically in Fig. 5, consists of a firetube package boiler simulator fitted with a precombustion chamber burner. The unit was modified to provide for reburning fuel and burnout air addition at various locations. The pilot-scale boiler simulator is rated at 0.9 MW heat input, capable of firing gaseous or liquid fuel. The boiler's radiant section is horizontal, 0.6 m in diameter, 3.0 m long, and cooled with the heat transfer fluid Dowtherm G®. Combustion gas exits the boiler through a vertical stack.

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[1]The major component of NO_x in the combustion gases is NO. In the pilot-scale research boiler (without a convective section), sampled stack gases leaving the radiant zone have a greater than 90 percent NO component of NO_x. In the fuel-rich zones within the preburner and boiler, NO accounts for nearly 100 percent of the NO_x. Therefore, only NO measurements are reported here.

[2]All NO concentrations are reported on a dry basis, corrected to zero percent O_2.

The precombustion chamber burner consists of primary fuel and primary air injectors, two 0.51 m diameter by 0.91 m long chamber modules, and a 0.25 m diameter transition section with eight radial ports for secondary air addition. To achieve rapid mixing in the precombustor the primary fuel is injected through a divergent nozzle and the primary air, which is not preheated, is passed through fixed swirl vanes. Primary fuel nitrogen is simulated by doping ammonia (NH_3) into natural gas or pyridine (C_5H_5N) into distillate fuel oil.

Secondary natural gas is injected through a water-cooled boom at three axial locations: 107, 30, and 5 cm from the boiler front face. The reburning fuel was injected uniformly into the primary combustion gas stream during reburning characterization tests using a spoked injector configuration, as described elsewhere [11]. Reburning natural gas was injected from a point source at the boiler centerline for the optimization tests described here. Burnout air was injected through eight radial ports in a water-cooled boom inserted down the boiler centerline through a rear flange, or through axial ports located on the boiler front face. When injected through the centerline boom, the location of the burnout air injection was nominally fixed at the 162 cm axial location.

The experimental facility is designed for independent control and measurement of each fuel, fuel dopant, and air stream. Stack and in-flame combustion gas speciation, temperature, and velocity are measured. NO is measured by chemiluminescence. Flame temperatures are measured using suction pyrometry. A Prandtl probe is used to measure combustion gas velocities.

Approach

To evaluate this multistaged process for low NO_x, high efficiency combustion, a three part experimental program was devised. First, baseline tests (i.e., no reburning) were performed to evaluate shortened burner (one-module) performance. First-stage stoichiometry and simulated primary fuel nitrogen content were varied. Results are compared with long burner (two-module) results. Second, parametric tests were performed to evaluate reburning effectiveness, under ideal mixing conditions, as a function of primary zone NO (NO_{pri}) level, reburn zone stoichiometry (SR_R), and simulated reburn fuel nitrogen content. These results have been previously reported [8-11] and are summarized here. Third, preliminary tests were performed with the shortened prechamber burner to optimize reburning application. These results are discussed and current tests on a new test burner are described.

BASELINE TEST RESULTS

At a primary burner firing rate of 0.6 MW and a nominal first-stage stoichiometry of 0.7, shortening the precombustion chamber burner length by removing one of the two modules decreased the bulk combustion gas first-stage residence time from 600 to 350 msec. In baseline tests (without reburning), first-stage stoichiometry was varied, with exhaust excess air

held constant at about 15 percent. Ammonia was doped into the natural gas fuel stream, resulting in a fuel nitrogen content of 0.66 percent. In Fig. 6 data are shown for both the short and long burner configurations. The minimum NO emission was observed at a first-stage stoichiometry of about 0.7, consistent with England's data at a similar scale test [2]. The sharp minimum in the curve indicates the sensitivity of NO emission to first-stage stoichiometry. The minimum NO emission increased from 50-75 to 200-250 ppm in going to the shortened burner. These ranges represent average NO emissions achievable given the small fluctuations in fuel and air flows.

The amount of NH_3 dopant was varied at the optimum first-stage stoichiometry (0.7) for both the short and long burner configurations. The data in Fig. 7 show that the short burner is more sensitive to fuel nitrogen content than the long burner. With no NH_3 addition, NO emission from the short burner was 90 ppm; from the long burner the NO emission was 40 ppm. These levels indicate the thermal NO component of the NO emission, coming from the molecular nitrogen (N_2) in the air. Because combustion of the hydrocarbon is less advanced at the secondary air addition location for the short burner, the peak temperatures in the boiler burnout zone are slightly higher than for the long burner. With the addition of NH_3 dopant the long burner NO emissions increased to 100 ppm, or a net 60 ppm contribution from the surrogate fuel nitrogen. The short burner NO emissions for high NH_3 dopant levels in the fuel stream approached 250 ppm, or a 160 ppm net increase due to fuel nitrogen. The reduced first-stage residence time resulted in less fuel nitrogen being reduced to N_2 in the fuel-rich precombustion chamber. As fuel nitrogen content increases above 2 percent the resulting increase in NO emissions becomes small.

Thus, an effect of halving the burner size was to increase minimum NO emissions for high nitrogen fuels from 100 to 250 ppm. Another effect was to move some of the flame back into the boiler, although still much of the heat release remains in the preburner. With a shorter flame length in the boiler with the preburner than with a conventional burner, reburning, which requires boiler volume, is an ideal technology for achieving additional in-furnace NO reduction. Before discussing preliminary tests combining the reburning and precombustion chamber burner technologies, reburning characterization tests are discussed.

REBURNING CHARACTERIZATION TEST RESULTS

Reburning involves staging a portion of the fuel and air streams downstream of the primary flame to reduce NO in the primary combustion gases. Parametric tests were performed previously [11] in the package boiler simulator in which primary NO was varied between 50 and 500 ppm and reburn zone stoichiometry was varied from 1.0 to 0.75. In these tests primary load was held constant at 0.6 MW, first-stage stoichiometry was fixed at 0.6 (off-optimum), and primary and burnout zone stoichiometries were held constant at 1.1. The secondary natural gas was injected at a 1.02 m axial location, just downstream of the visible primary flame. Using a spoked fuel injector, natural gas was injected to match the flux of free oxygen from the primary zone, thereby providing radial uniformity in the

reburn zone stoichiometry. Burnout air was added at the 1.62 m axial location. Primary NO was varied by varying the primary fuel NH_3 dopant level. Reburn zone stoichiometry was varied by varying the reburn fuel and air flow rates. This procedure provided sufficient control to measure the maximum reburning effectiveness in the package boiler simulator.

Results from these natural gas reburning tests are summarized in Fig. 8. The strong dependence of NO reduction on primary NO is in agreement with the results reported by Chen [4] and in conflict with the MACT claim [7]. Analysis of the data in Fig. 8 suggests that the overall NO destruction rate has a partial order with respect to primary NO of 1.5 to 1.6. That is,

$$d[NO]/dt = C\ [NO_{pri}]^{1.5\text{-}1.6}$$

Additional data were taken to evaluate reburning fuel nitrogen effects [9]. From this data a contour map was drawn depicting the relationship between overall NO reduction by reburning and two controlling parameters: reburning fuel nitrogen content and primary NO level. In Fig. 9 it is shown that 50 percent NO reduction is not possible for primary NO levels less than 140 ppm. For NO levels less than 250 ppm, fuel nitrogen content limits NO reduction. For example, at an initial NO level of 200 ppm, reburning with fuels exceeding 1 percent in fuel nitrogen results in increased NO emissions.

Based on these results from reburning tests performed under idealized mixing conditions, it was hypothesized that reburning applied in tandem with the precombustion chamber burner could produce NO emissions of less than 150 ppm for gaseous and liquid primary fuels with up to 4 percent fuel nitrogen.

PRELIMINARY PROOF-OF-CONCEPT TEST RESULTS

Preliminary tests were performed to evaluate the concept of natural gas reburning of combustion gases from a half-sized precombustion chamber burner. A primary NO level of 260 ppm was maintained by operating the burner at an off-optimum stoichiometry of 0.65 to reduce the amount of fixed nitrogen dopant (NH_3) required to achieve this emission. This NO level represents the maximum emission of the half-sized burner when burning fuels with up to a 4 percent fuel nitrogen. Primary flame zone stoichiometry leaving the preburner was fixed at 1.1. The locations of staged fuel and air addition were varied.

Figure 10 shows the effect of reburn fuel injection location on NO emissions. Reburning fuel was added at the 107, 30, and 10 cm axial locations in the boiler. Burnout air was added at 168 cm. From Fig. 10 it was observed that slightly lower NO emissions were achieved injecting the reburn fuel downstream of the primary flame. However, even injecting reburn fuel at the outlet of the precombustion chamber resulted in significantly reduced NO emissions. The data suggest that reburn fuel can be injected at the boiler front face and still achieve NO emissions of less than 150 ppm.

Figure 11 shows the effect of burnout air injection location on exhaust NO levels. With reburning fuel injected at 30 cm, air was injected through axial ports on the boiler front face. The results show only slightly higher NO emissions than with deep-staged (168 cm) burnout air. Thus, injecting burnout air from the boiler front face results in NO emissions that approach the 150 ppm level.

An EPA program to optimize burner design and operating parameters is ongoing. A new burner system has been designed and installed so that reburning fuel and air can both be injected from the boiler front wall, with variable angle of injection. The preburner has been made vertical to increase preburner temperatures by reducing radiative heat loss to the boiler and by taking advantage of thermal buoyancy effects. The new design also contains a greater number of small modules so that preburner size can be varied over a wider range. Tests will be performed to optimize reburning fuel and air injection parameters (angle, velocity, flow rate). Primary zone stoichiometry will also be varied to optimize primary fuel hydrocarbon destruction and primary fuel nitrogen conversion.

DISCUSSION AND CONCLUSION

Based on the data presented in Figs. 7 and 9, predictions can be made of NO emissions as a function of primary and secondary fuel nitrogen content. However, by injecting fuel and air on the front face of the boiler a reduction in reburning effectiveness was observed (Figs. 10 and 11). With 250 ppm primary NO, a 42 percent reduction was achievable for reburning with a nitrogen-free fuel at the boiler front face, versus 55 percent reburning downstream of the primary flame with uniform injection (Fig. 9). Though insufficient data are available to make a new contour map of reburning effectiveness versus primary NO for reburning application from the boiler front face, it is conservatively assumed here that reburning effectiveness is reduced by 10 to 15 percent from downstream uniform reburning application. Based on this assumption and the data in Figs. 7 and 9, Fig. 12 shows reburning effectiveness versus primary and secondary fuel nitrogen content. For natural gas reburning, this information is replotted in Fig. 13. The multistaged burner design used in this study significantly improves NO_x control technology currently in use.

Further testing is required to confirm these predictions and optimize controlling parameters. Further testing is also required to determine the applicability of using this system to incinerate highly nitrated waste. Tests are ongoing at EPA to investigate these areas.

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Figure 1. NO_x emissions from stationary combustion sources as a function of fuel nitrogen content. Uncontrolled (pre-NSPS) emissions are shown, as are emissions from sources with current NO_x control combustion modification technologies employed.

Figure 2. Field test results using a full-scale commercial prototype burner for crude oil-fired steam generators used for thermally enhanced oil recovery (TEOR). NO, CO, and smoke emissions are shown. From Ref. 2.

(a) Prototype burner design.

(b) Field test results.

Figure 3. NO_x emissions at optimized burner conditions from bench-, pilot-, and full-scale tests as a function of first-stage residence time. From Ref. 2.

Figure 4. The reburning process.

Figure 5. Pilot-scale package boiler simulator modified with precombustion burner and conventional reburning application.

Figure 6. Influence of first-stage residence time on NO emission for short and long preburner configurations.

Figure 7. Influence of fuel nitrogen content on minimum NO emission for short and long preburner configurations.

Figure 8. NO reduction for natural gas reburning application. From Ref. 11.

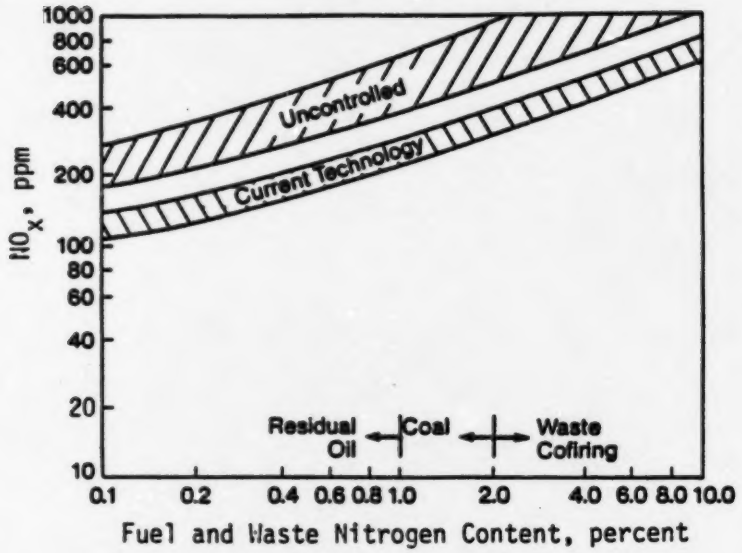
Figure 9. Contour map of optimum NO reduction by reburning. From Ref. 9.

Figure 10. NO emissions as a function of reburn zone stoichiometry for various reburn fuel injection locations.

Figure 11. NO emissions as a function of reburn zone stoichiometry for various burnout air injection locations.

Figure 12. Contour map of predicted NO emissions from the multistaged burner used in this study.

Figure 13. NO_x emissions from this study compared to those achieved by control technologies currently in use.



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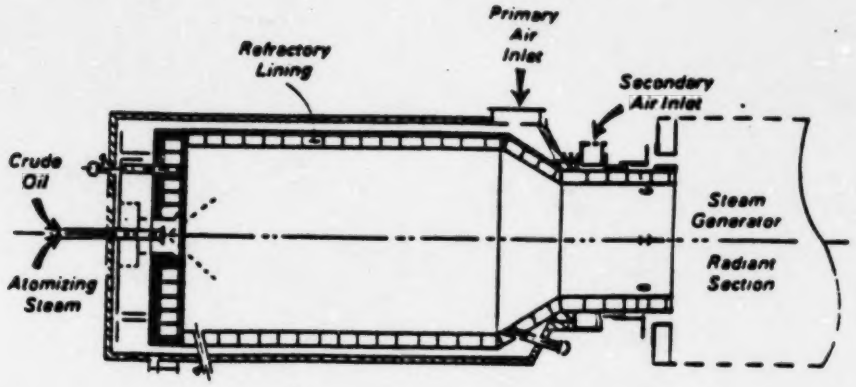
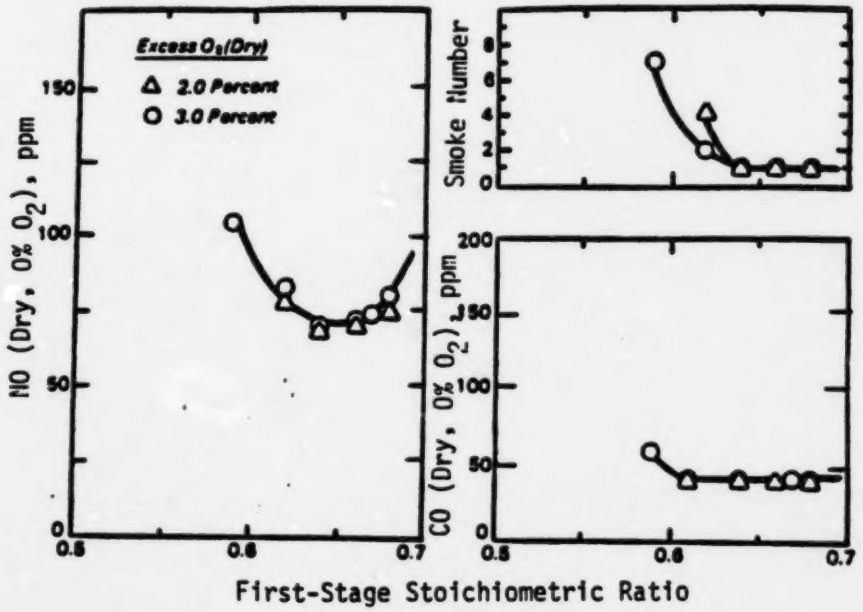


(a) Prototype burner design.



(b) Field test results.

Figure 2. Field test results using a full-scale commercial prototype burner for crude oil-fired steam generators used for thermally enhanced oil recovery (TEOR). NO, CO, and smoke emissions are shown. From Ref. 2.

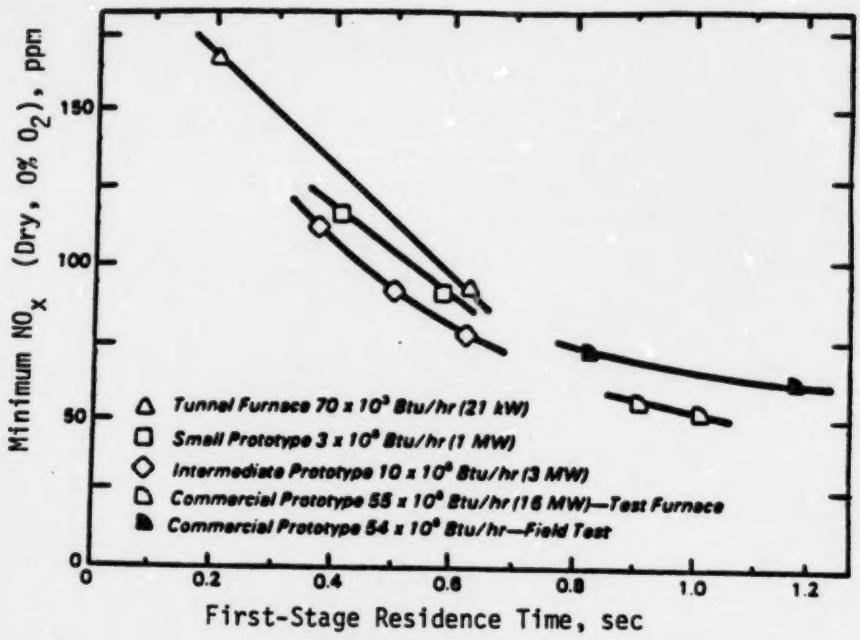


Figure 3. NO_x emissions at optimized burner conditions from bench-, pilot-, and full-scale tests as a function of first-stage residence time. From Ref. 2.

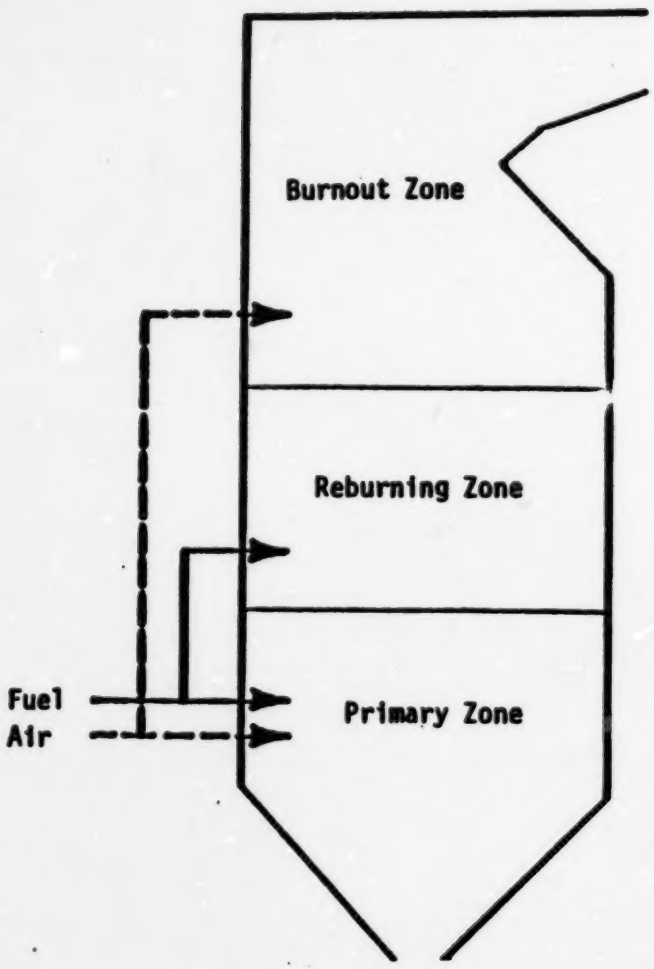


Figure 4. The reburning process.

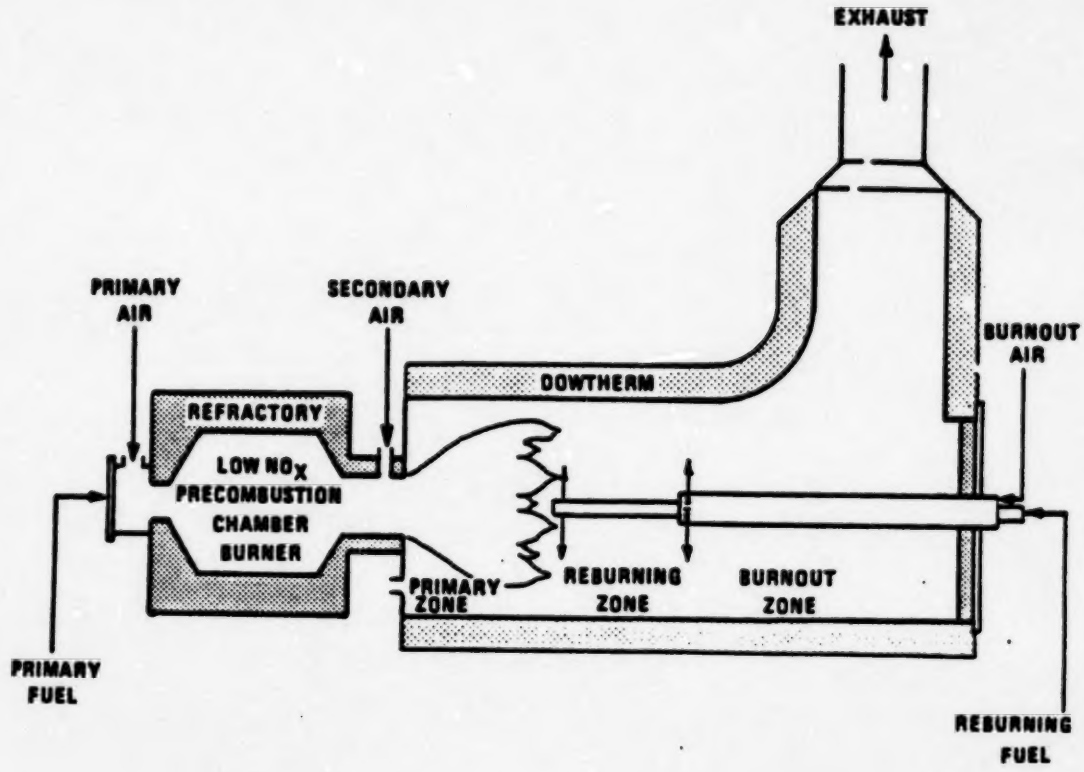


Figure 5. Pilot-scale package boiler simulator modified with precombustion burner and conventional reburning application.

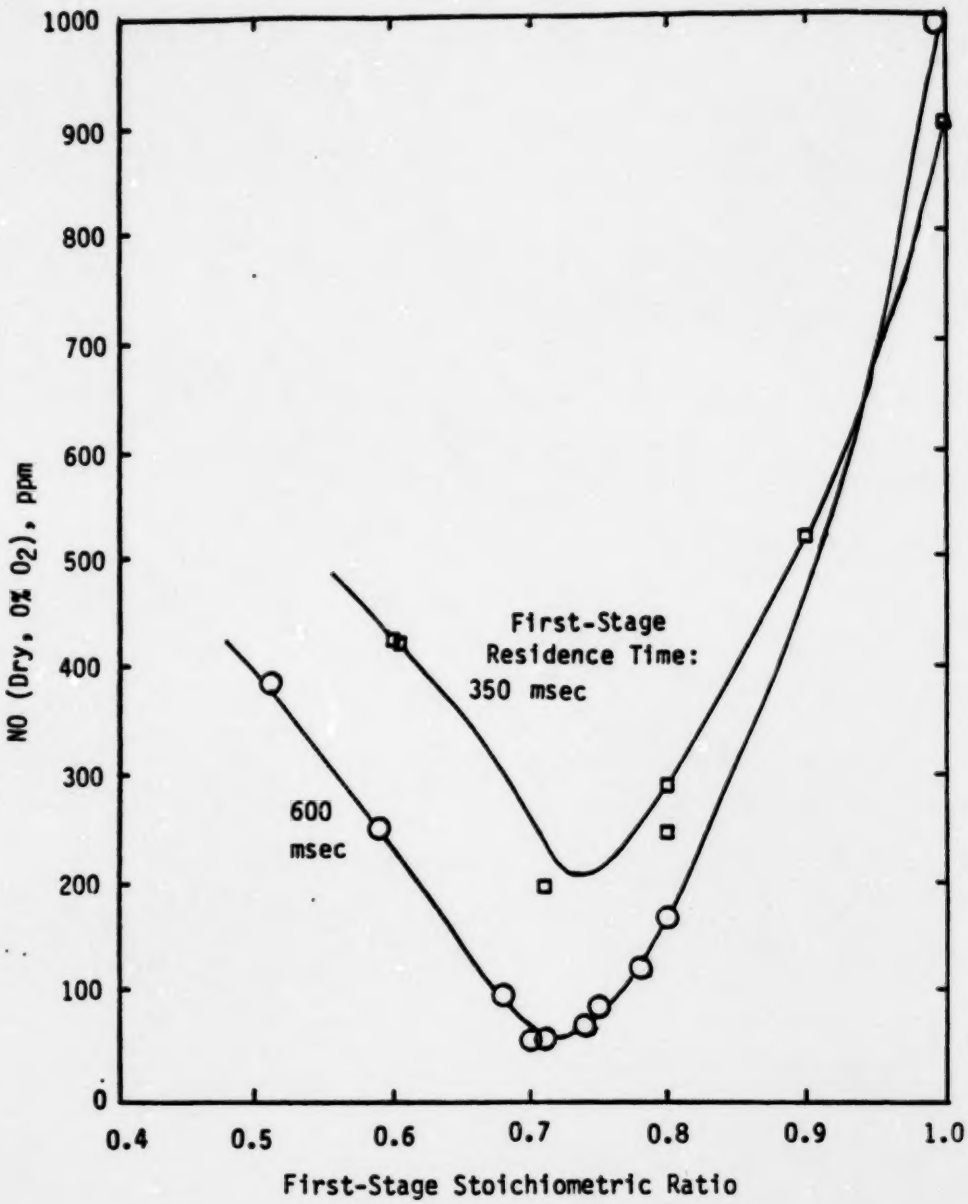


Figure 6. Influence of first-stage residence time on NO emission for short and long preburner configurations.

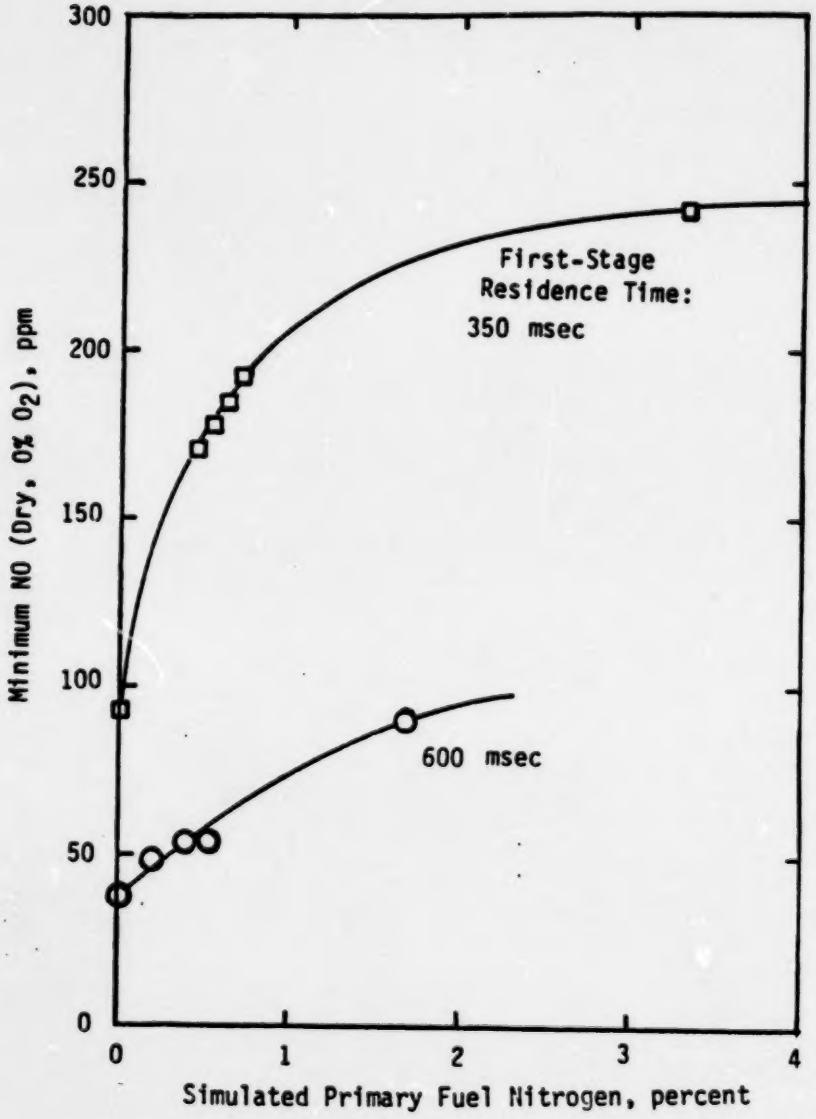


Figure 7. Influence of fuel nitrogen content on minimum NO emission for short and long preburner configurations.

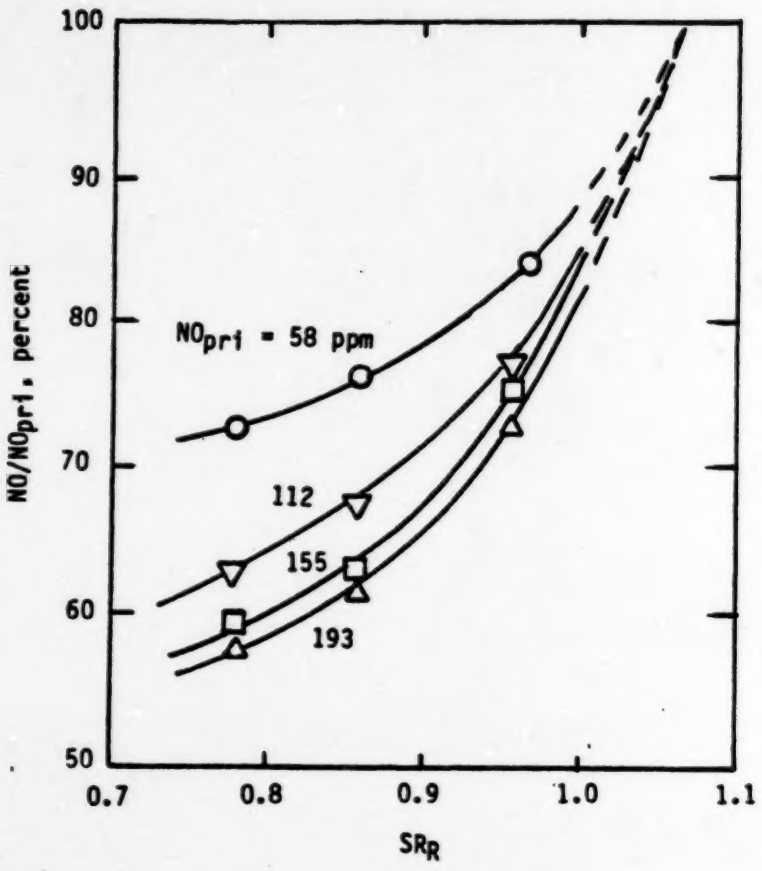


Figure 8. NO reduction for natural gas reburni g application. From Ref. 11.

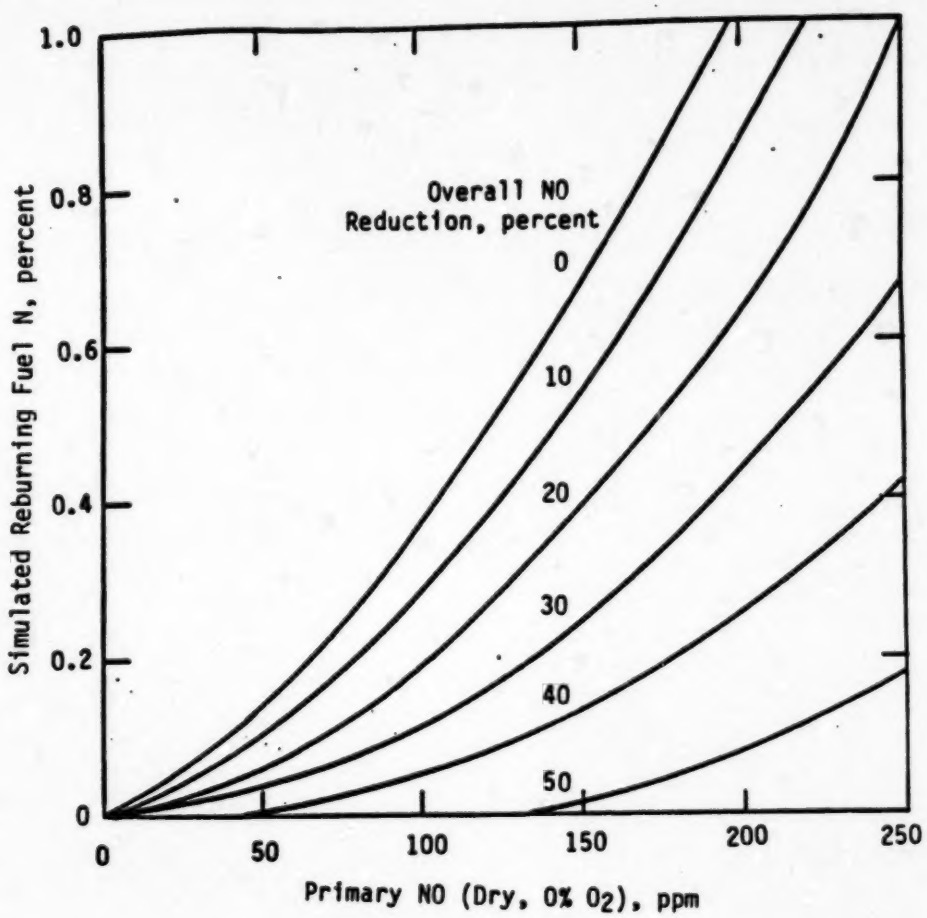


Figure 9. Contour map of optimum NO reduction by reburning. From Ref. 9.

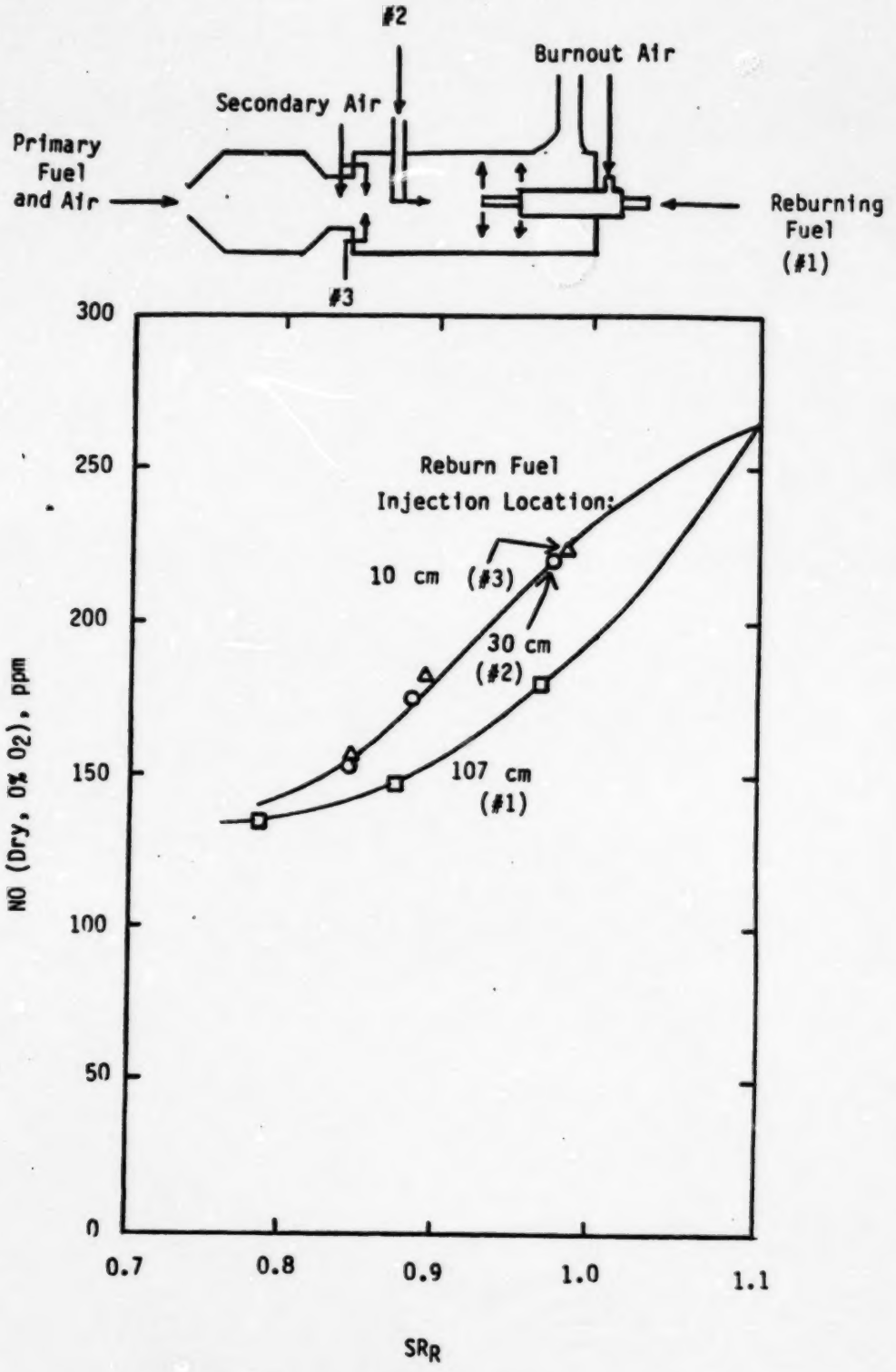


Figure 10. NO emissions as a function of reburn zone stoichiometry for various reburn fuel injection locations.

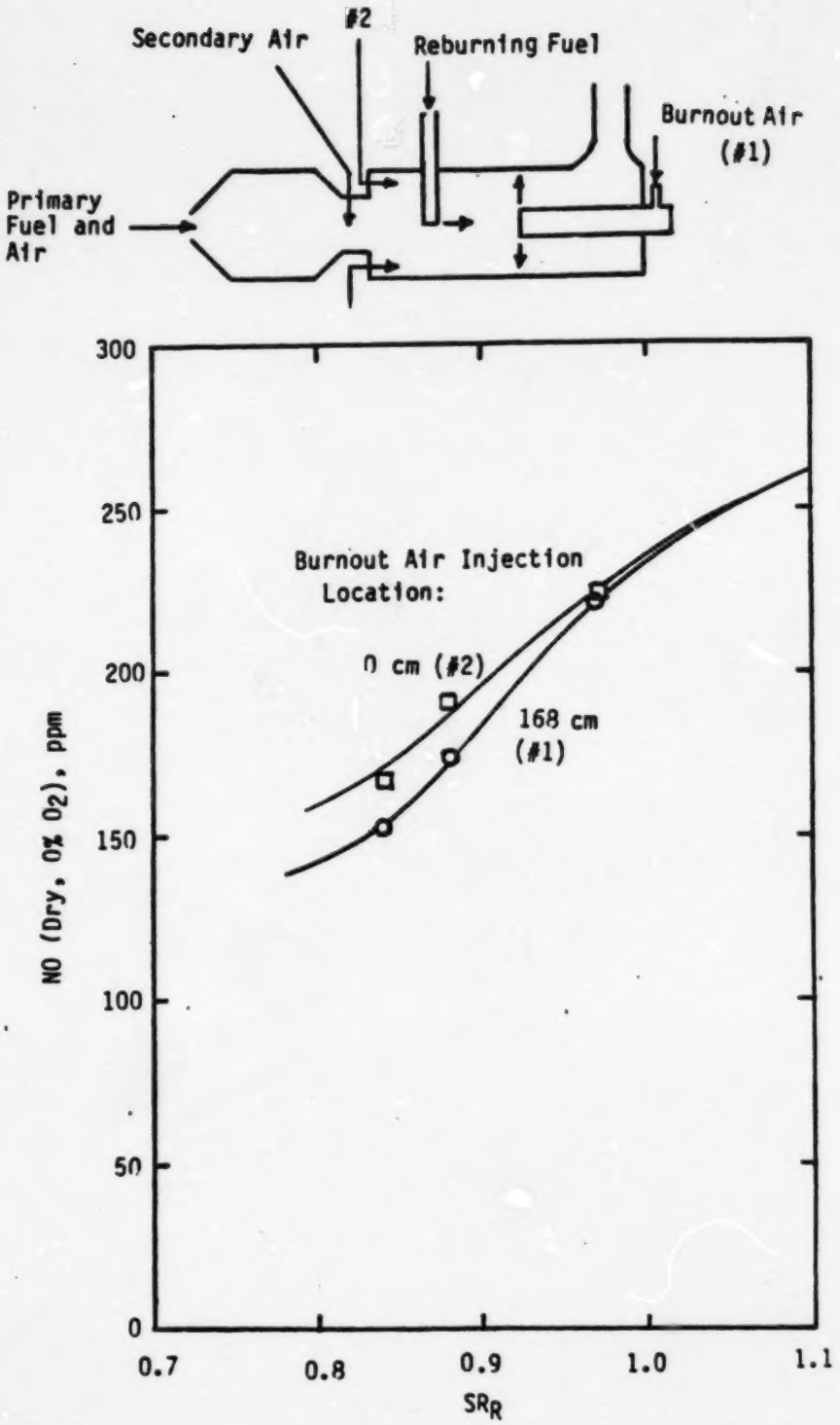


Figure 11. NO emissions as a function of reburn zone stoichiometry for various burnout air injection locations.

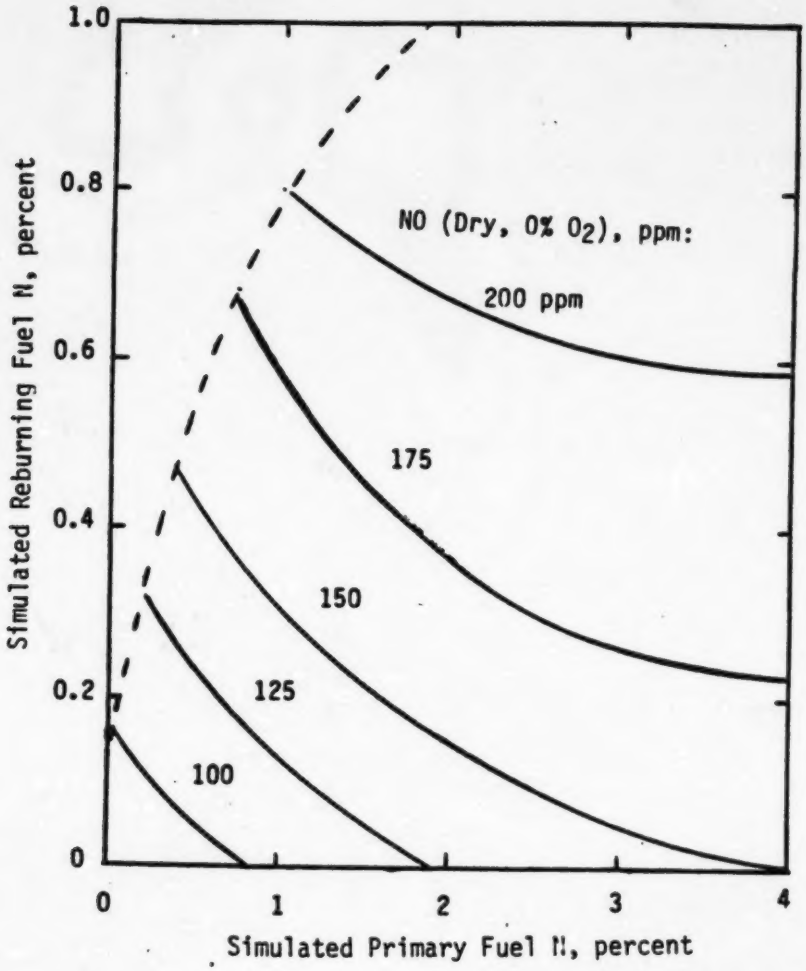


Figure 12. Contour map of predicted NO emissions from the multistaged burner used in this study.

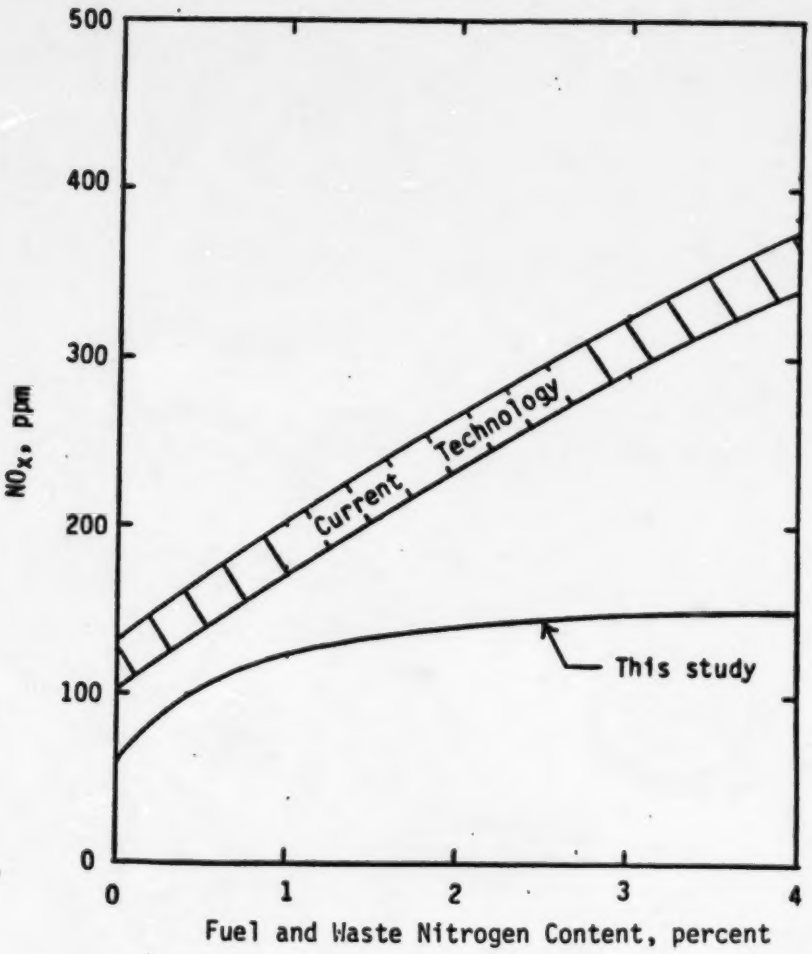


Figure 13. NO_x emissions from this study compared to those achieved by control technologies currently in use.